

Metallurgical Examination of an AMTEC Power Unit

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Abstract. Two AMTEC power units fabricated by Advanced Modular Power Systems, Inc. using a cold end condenser manufactured by Creare, Inc. which operated for 342 hours and 575 hours were dissected and examined. The maximum output power for both units varied from approximately 68 to 25 mW and 2.6 to 1.8 watts for the respective units during their operational life prior to shutdown. The corresponding BASE tube and condenser temperatures were in the range of 730 C and 390 C for one unit and 705 C and 270 C for the other. The power units were constructed with a stainless steel housing and stainless steel sheathed molybdenum wick. Analysis showed that the internal sodium was primarily distributed near the condenser end of the power unit extending out to a distance of 2.5 cm. No significant amount of sodium was observed in the BASE tubes or plenum. A similar sodium distribution was observed in the second AMTEC cell with a Creare condenser which operated for 575 hours. The wick was sliced into 2 to 3 mm sections and analyzed using a SEM and X-ray fluorescence to determine its sodium distribution. The sodium distribution along the wick from the condenser to the base of the evaporator was observed to be continuous throughout. The failure mechanism was determined to result from a fracture of the structural joint at the BASE tube braze seal on several of the tubes.

INTRODUCTION

Long term planetary missions require power sources capable of operation out to 15 years or more. Present thermoelectric power systems have a proven reliability over such long periods but produce a relatively small power output at a very low efficiency. Alkali Metal Thermal to Electric (AMTEC) power systems offer two to three times the efficiency of thermoelectric systems. However long term operational tests must be conducted to determine reliability and performance degradation mechanisms. Two AMTEC power units containing 6 internal beta alumina solid electrolyte (BASE) tubes noted as Creare 1 and Creare 2 were operated for 342 hours and 575 hours respectively in vacuum. Special high efficiency cold end condensers were fabricated as part of the cell design by Creare Inc. Aside from external thermocouples used to monitor the external temperature, the power units were instrumented with two internal thermocouples inserted into approximately 0.079 cm outer diameter stainless steel wells to a depth of 3.97 cm in one of the 6 BASE tubes and 1.59 cm into the sodium evaporator. The wells positioned the thermocouples at the top inside of one of the cells and pressed against the top of the evaporator. One power unit was operated at a BASE tube temperature of about 705 C while the other operated at a BASE tube setpoint of about 730 C. Tests were discontinued on Creare 1 due to a very low output power and short circuit current. Operation of Creare 2 was halted when the original output power level could not be regained after the heater providing power to the unit failed. The furnace test setup used for both power units is shown in Figure 1. One of the power units can be observed installed inside the cylindrical insulation package prior to insertion of the surrounding insulation and heater unit. Both cells were installed with the condenser end oriented downward and the heated end on top. The operational performance of Creare 1 and Creare 2 are depicted in Figures 2a and 2b. The power output from Creare 1 was about a couple of orders of magnitude less than Creare 2. The corresponding variation in the condenser and BASE tube temperatures during operation are shown in Figures 3a and 3b. The BASE tube temperature was measured using a thermocouple inserted into a well that was fabricated as part of the unit design for this purpose. The condenser temperature was measured using a thermocouple pressed tightly against the cold end unit surface using a screw sleeve attached to the unit to protect the anode electrode.



FIGURE 1. AMTEC Power unit furnace test setup.

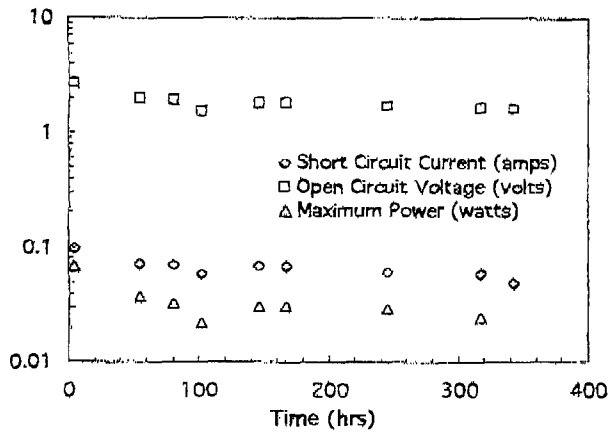


FIGURE 2a. Creare 1 electrical performance.

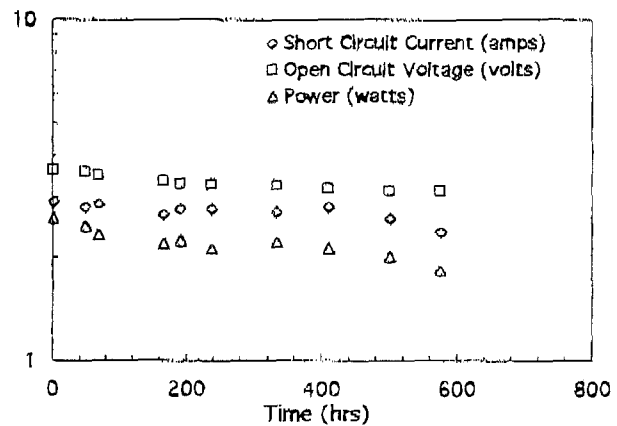


FIGURE 2b. Creare 2 electrical performance.

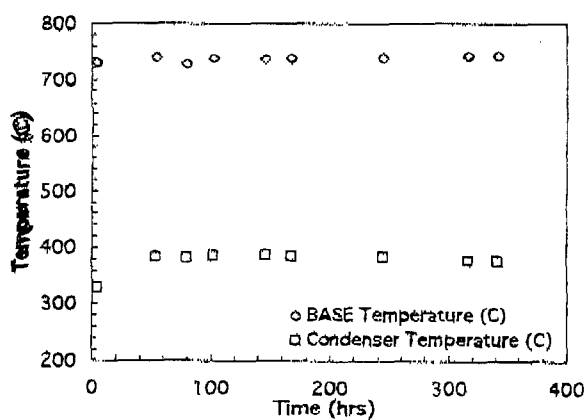


FIGURE 3a. Creare 1 temperatures.

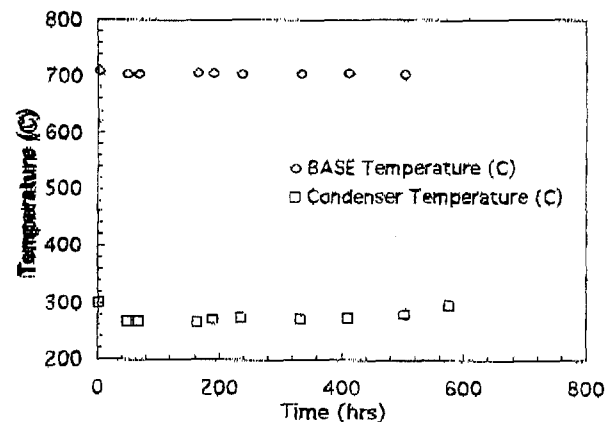


FIGURE 3b. Creare 2 temperatures.

ANALYSIS

Both AMTEC power units were slowly dissected using a diamond saw (e.g. Figure 4) inside of a special sodium glove box containing recirculating oxygen and moisture free argon gas. Figures 5a and 5b show internal views of

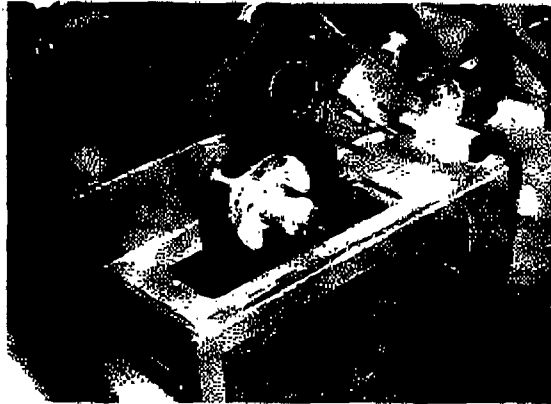


FIGURE 4. AMTEC Power Unit and diamond saw.

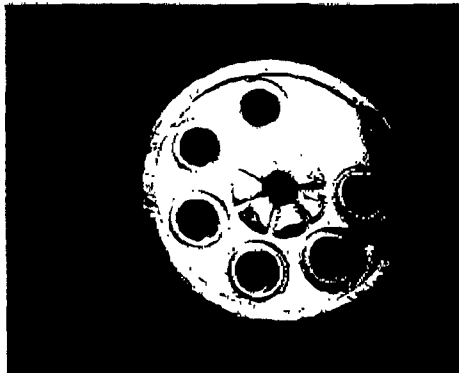


FIGURE 5a. Dissected plenum view.



FIGURE 5b. Creare 1 cross-sectional view.

the Creare 1 power unit. The glistening coating observed on the interior surfaces is due to the high purity low vapor pressure oil used as a cutting lubricant. Figure 5a shows the rear of the BASE tubes after the hot side plenum that contains the sodium vapor under normal operation was removed. The central orifice is the exit path for the expanding sodium vapor from the evaporator. The six peripheral openings lead into the individual series connected BASE tube cells. Under visual observation no coating was apparent on any of the surfaces within the plenum. Several small sodium nodules under 1 mm in diameter were found on the interior surface of one of the tubes near the top inside and in the area of the evaporator. No sodium accumulation was observed in the transition tubes from the plenum to the inside of the BASE tube cells. A thin sodium coating was apparent on the interior electrode grid and upper (i.e. cooler) end of the BASE tubes. The internal sodium was observed pooled near the cooler condenser end of the power unit and extending up approximately 3.2 cm on the exterior surface of the wick which is the central tube in Figure 5b (e.g. the offset tube is the main cathode electrode). Sodium on the interior walls extended about 0.3 cm past the 2nd thick strengthening side wall band (near the left side of Figure 5b). Visual observation in contrast showed no apparent sodium on the exterior surfaces of the BASE tube electrodes (i.e. cathodes) or on any of the internal surfaces near the hotter regions of the power unit (e.g. in the right portion of Figure 5b). During the examination of the interior of the BASE tubes from the plenum end there was an indication that several were broken. Combined electrical resistance measurements across each of the individual cells and along the string of cells implied one or more breaks along the cell string. External examination showed that two adjacent tubes were detached at the point where the BASE tube was braised sealed to the slightly larger diameter alumina insulator that can be seen near the right edge of Figure 5b. A similar examination conducted on Creare 2 discovered two breaks at the BASE tube braise seal at the opposite end of the cell string. The braising surface of one of the broken tubes can

be observed in Figure 6. The relatively smooth surface appears to indicate that the detachment was due to a failure of the braise seal as opposed to a break in the BASE tube.



FIGURE 6. View of severed BASE tube braise seal surface.

The possible cause of the poor operation and failure of these AMTEC power units can be attributed in part to the failure of the braise seal. However sodium transport in the wick could also prove problematic. The wick is Creare 1 was dissected to observe the sodium distribution within its structure. The wick was cut into 15 portions of approximately 2 to 3 mm using a diamond saw. Each wick piece was slowly cut and allowed to break in a slightly irregular manner to minimize smearing of sodium across the cross sectional surface. The unpolished surfaces of each cut wick section was photographed using a scanning electron microscope (SEM) and at the same time subjected to elemental analysis using X-ray florescence. Figures 7 through 9 show the secondary electron SEM photos and back scattered electron SEM photos of the wick cross-section along side the X-ray florescence map of the sodium distribution. The secondary electron photo provides a good image of the surface topography while the back scattered electron image contrasts the regions of heavier atomic mass elements from those of the lighter elements. The lighter regions of the back scattered images reflect the iron dominated regions of the stainless steel wick sheath while the darker area in the middle region of the wick cross section depict areas where sodium is present. The back scattered images area reflecting the sodium presence can be contrasted with the sodium distribution mapped in the 3rd photo in each series which is the x-ray florescence image. The darker areas in each x-ray image are due to electron shadowing and do not reflect a lack of sodium. Figure 7a-c shows the cross sectional surface at a point 3 mm from the point where the wick was inserted into the cold side condenser (i.e. 50 mm from the start of the evaporator as can be seen in Figure 5b). In contrast, Figure 8a-c shows the cross section at the middle of the wick or at a point 21 mm from the condenser (i.e. 32 mm from the start of the evaporator). Finally Figure 9a-c shows the cross section at 50 mm from the condenser and 3 mm from the evaporator. In all three cases the sodium distribution appears uniform across the surface. The uniformity however does not necessarily reflect the efficiency of sodium transport through the wick, only that sodium at some point during the operation has coated the molybdenum wick throughout.



FIGURE 7. Creare 1 wick cross sectional 3mm from condenser; (a) secondary electron SEM photo, (b) back scattered electron SEM photo, (c) X-ray florescence map of sodium distribution.



FIGURE 8. . Creare 1 wick cross sectional midway from condenser; (a) secondary electron SEM photo, (b) back scattered electron SEM photo, (c) X-ray florescence map of sodium distribution.



FIGURE 9. . Creare 1 wick cross sectional 3mm from the evaporator; (a) secondary electron SEM photo, (b) back scattered electron SEM photo, (c) X-ray florescence map of sodium distribution.

CONCLUSION

Based on observation of sodium distribution in the wick and the breaks in the BASE tube assemblies at the alumina-BASE braze seal, the failure of Creare 1 and 2 can likely be attributed to a mechanical failure mechanism. This supposition however does not preclude any problems with the transport efficiency of sodium through the wick as having an effect on the performance of the AMTEC power unit. Since the Creare 1 power unit had only operated for 342 hours before shutdown it's apparent that Sodium does uniformly coat the interior of the wick early in the operational life.

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